RADIATION DAMAGE AND PHASE INSTABILITY IN IRRADIATED STAINLESS STEEL*

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The radiation response of metallic alloys can be strongly dependent on specific solute elements. Void swelling and phase instability of the matrix are two primary concerns in the design of nuclear reactors. A 316 stainless steel, LS1A, with greater than nominal levels of silicon and titanium has been developed which exhibits high resistance to swelling under ion irradiation. The origin of this swelling resistance and the roles of silicon and titanium have been investigated in the current study.

Figure 1 illustrates the evolution of the damage structure in LS1A under nickel ion irradiation at 625°C. At low dose [~ 1 dpa, Fig. 1(a)], faulted interstitial dislocation loops (43-nm-av diam) are observed. We have previously reported that significant solute silicon segregation (approaching 7.0 at. %) in the vicinity of the loop fault plane occurs at such doses in LS1A. Below 10 dpa, precipitates appear to replace the loops in similar sizes and densities. At 70 dpa [Fig. 1(b)] there is no swelling and the matrix phase instability has produced $\sim 5\%$ volume fraction precipitate. Under similar conditions, swelling in a nominal 316 stainless steel is $\sim 4.2\%$ and no phase instability is observed. No void nucleation is observed in uninjected LS1A up to dose levels of 600 dpa [Fig. 1(c)], at which the swelling in a nominal 316 stainless steel is $>100\%$. The precipitate volume fraction is $\sim 6\%$, indicating a saturation in matrix phase instability.

During irradiation two precipitates occur; both are cubic phases with lattice parameters ~ 1.1 nm and both are rich in silicon and nickel. One precipitate is G phase, an fcc silicide isostructural to $M_{23}C_6$; while the other precipitate is eta phase, a diamond cubic silicide isostructural to M_6C . Figure 2 gives typical EDS spectra of these two phases from extraction replicas. Average compositions (for 3-5 particles) are given in Table 1. The silicon segregation to faulted loops is believed to result in supersaturation and precipitation of the G and eta phases.

Injection of helium can strongly modify the evolution of the damage microstructure. For simultaneous helium injection at 0.2 at. ppm He/dpa, void nucleation is observed in association with the irradiation-induced precipitates at 10 dpa. At 70 dpa [Fig. 3(a)], 3.5% void swelling is observed in irradiated LS1A. Preinjected helium has a vastly different effect on the damage structure. At 70 dpa with 14 at. ppm He preinjected [Fig. 3(b)], a significant population of faulted loops still exist along with a bimodal cavity size distribution. A high density ($\sim 10^{21} m^{-3}$) of very small 2-nm-diam cavities are observed together with a low density of larger 10-nm diam cavities. The maximum swelling is less than $1.0 \times 10^{-4}\%$. Little or no phase instability is observed. However, if 14 at. ppm He is injected after the phase instability begins (~ 10 dpa), the resultant damage structure at 70 dpa [Fig. 3(c)] is very similar to that for simultaneous helium injection. Voids ~ 60 nm in diameter at a density of $1.2 \times 10^{20} m^{-3}$ result in 1.6% swelling, while 3.2% volume fraction precipitate is present.

The role of silicon in the swelling resistance of LS1A may involve trapping of point defects which from theory would increase defect recombination. The role of titanium in the swelling resistance of LS1A involves trapping and also

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the gettering of interstitial impurities (C,N,O) which would normally stabilize the void nuclei. It is obvious that phase instability alone is not a sufficient condition for a loss of swelling resistance. The presence of helium is required for void nucleation in LS1A.

Table 1. Precipitate Compositions (at. % for Z > 11)

	Si	Ti	Cr	Mn	Fe	Ni	Mo
G phase	27.9	N.D.	6.4	2.1	6.0	56.9	0.7
η (eta) phase	16.7	1.0	30.5	1.4	18.0	27.1	5.3

Fig. 1. Damage structure of LS1A irradiated at 625°C (a) 1, (b) 70, (c) 600 dpa.

Fig. 2. Typical EDS spectra of extraction replica on copper grid. (a) G phase at 30 dpa, 625°C, (b) eta (η) phase at 70 dpa, 675°C.

Fig. 3. Influence of 14 at. ppm He on LS1A damage structure at 70 dpa. (a) Simultaneous He injection, (b) 14 at. ppm He preinjected (inset 7 $\times$), (c) injected at 10 dpa.

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